Does the world need general-purpose programmable photonics?

(Invited paper)

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General-purpose programmable can provide an easily accessible technology for prototyping new photonic functions on chip, enabling innovations in new applications without the steep entry cost of full-custom photonic integrated circuits.
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Programmable photonics is the emerging research field of photonic chips where the flow of light can be reconfigured through an electronics and software layer [1]. This contrasts with traditional photonic chips, which usually have a fixed connectivity and are designed for one particular application. To assess the potential of such reconfigurable circuits, we draw a comparison between the field of integrated photonics and the field of integrated electronics.

Silicon electronics has become pervasive in most aspects of our lives. Our technologically advanced society relies on electronic chip technology for data processing, computation, communication, and sensing. The versatility of electronic chips has even made them more cost-effective for many simple management and control tasks than traditional mechanical or hydraulic systems. It would be impossible to imagine our society without electronics. The economies of the semiconductor industry have enable the fabrication of massive amounts of electronic chips.

Photonics is slowly assuming a similar role. We already know that the ubiquitous internet communications are supported by a hidden network of high-bandwidth fiber-optic links, but we also use light for diverse functions in sensing, data storage and manipulation of our environment. Like in electronics, these optical functions are being integrated on chips, which often make use of similar fabrication technologies as electronic chips, especially when it comes to so-called 'silicon photonics' [2].

Even though many of the critical building blocks of photonics and electronics originated in the same period between 1945 and 1960 (most notably the laser and the transistor) one can argue that the ecosystem of photonic chips is lagging several decades behind that of their electronic counterparts. This can be observed through various metrics:

- **The diversity of technologies**: While one can argue that photonic chips today use a much wider range of material systems (Silicon, III-V semiconductors, silica, polymers, LiNbO3, silicon nitride) compared to electronics (99.9% silicon), there is an enormous diversity in industrial electronic chip platforms, covering 2-3 orders of magnitude in transistor gate length (so-called 'technology nodes'), with flavors for high-voltage, low-power, high-speed or radiation hardened circuits, with both analog and digital functions. For most electronic chip designers, it is much easier to find a platform with the desired characteristics than it is for a photonics designer. For photonics designers, there is of course the additional complication that different use cases might require different optical wavelengths, which limits the materials that can be used.

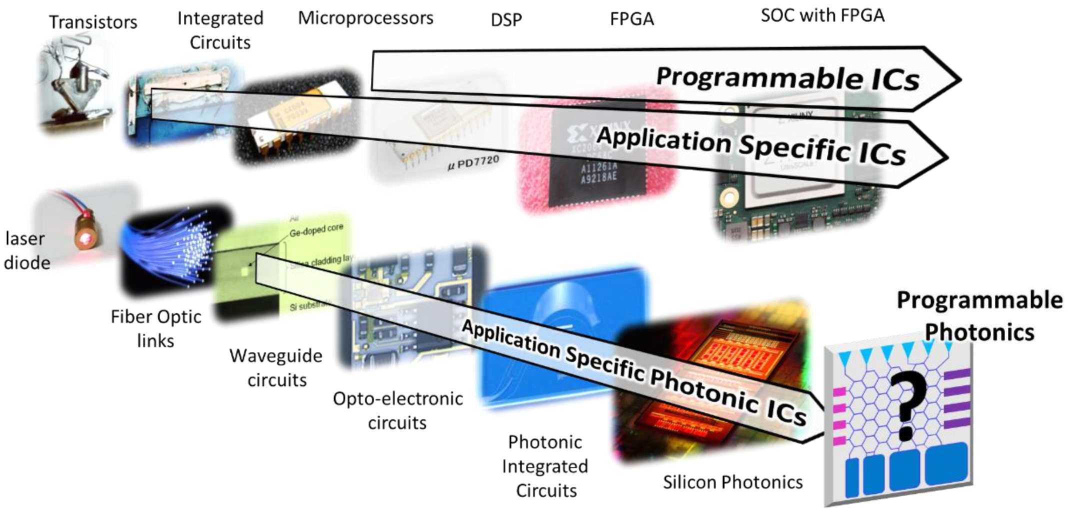

Figure 1: Photonics and electronics follow the same scaling path in circuit complexity, but the success of electronics has been multiplied by programmable hardware, which today is misssing in the field of photonics

- **The manufacturing volumes**: The numbers of chips being churned out by a single modern electronic foundry dwarf the total worldwide production volume of photonic chips. As a result, the benefits of scale are often not large enough to really bring down the cost of photonic chip production, even in situations where the photonics is fabricated in the same fab facilities as electronics. As a result, the maturity of fabrication processes for photonic chips is often much lower.
- **Diversity in applications**: today, we find electronics in applications well beyond the field of "computing". The applicability of electronics to make traditional hardware 'smart' has played in tandem with the economies of wafer-scale fabrication to make it possible for product developers to incorporate electronic chips in even the cheapest consumer goods.
- **Design and prototyping**: One of the aspects that allowed the widespread proliferation of electronics is the capability to design a complex chip with many analog and digital functions, and accurately predict how this chip will behave after fabrication. The rapid evolution of electronic design automation (EDA) tools in the 1990s and 2000s, together with the introduction of reusable 'IP blocks', has enabled first-time-right design, lowering the threshold for new designers to use the technology. This, in turn, has accelerated the prototyping of new electronic functions for new applications. In photonics, the evolution of the design tools is rapidly evolving in the same direction, but the lack of standards and the lower maturity of the fabrication processes make first-time-right design for photonic chips an elusive goal [3]. While the prototyping time of a new photonic chip is similar as a new electronic chip (1-2 years), the photonic chip will often require multiple iterations.
- **Programmability and Software**: One of the most prominent features of many electronic chips is their programmability, which makes it possible to adjust, modify or redefine the functionality of the hardware after fabrication [4]. This can be as 'programmable hardware' like field-programmable gate arrays (FPGA), specialist chips (e.g. digital signal processors – DSP) or general-purpose microprocessors. Most photonic chips today are designed for specific functions and cannot be reconfigured after fabrication. True, many chips include electro-optic tuning mechanisms to finetune the chip response, or can be used to switch optical signals, but they are still built to perform specific functions. In contrast with electronic FPGAs and microprocessors, new photonic functionality will require the design and fabrication of a new photonic chip.
- **Education and Community**: the success of electronics has, over the past decades, led to widespread educational programs in electronics engineering, but also in computer and Software Engineering. This has created an enormous worldwide community to innovate in these technologies, create new applications, drive standards and overall push the field forward. The well-known Moore's law can be seen as both a cause and a consequence of this widespread adoption. While optics as a field is much older than electronics, it has not seen this rapid growth, and it turns out that there is also a considerable gap between traditional optics and the newer chip based 'photonics'. Today, for every engineer that can design a photonic chip, there are at least 100 electronic chip designers, and probably 1000 software engineers to program their functionality.

If we look at the above metrics, we can clearly see that many of those are correlated, and mutually reinforcing. Today, we see that the field of integrated photonics is rapidly growing, but it lacks several enablers that have been crucial for the widespread adoption of electronics. One of the key factors that made electronics successful as a driver of innovation, including the emergence of a large "Maker" community, is its programmability. Programmable electronics makes it possible to experiment, develop and prototype many new applications without the prohibitively expensive design-fabricate-test cycles of custom electronic chips. Even though programmable electronics are generally larger, slower, and consume more power that optimized application-specific integrated circuits (ASICs), they are in many cases good enough, and can be more cost-effective in low to moderate volumes.

Today, this low-threshold model for developing new application is completely absent in integrated photonics. There is simply no photonic equivalent for general-purpose FPGAs or microprocessors. Because of this, every new idea for a photonic innovation that could be implemented on a chip, and that could lead to new applications and products, has to go through numerous design-fabrication-test cycles. This is a costly and cumbersome process, and as a result the spread of photonic chip technologies is processing at a slow pace, except in the few fields where it is already successful, in particular fiber-optic communications.

Programmable photonics, or more precisely general-purpose programmable photonic chips could dramatically lower this adoption threshold. If such chips are available as off-the-shelf components at a modest price point (because they can be fabricated in much higher volumes than application specific chips) the lead time for experimenting with this technology is reduced from a months/years to mere days. This is conducive for agile product development and innovation, as new ideas can be prototyped through software development and iteratively tested with actual users. Just like with electronics, there might be many use cases where the performance of these programmable chips is adequate. In other cases, they could help to identify the performance gap, and if the market drive is strong enough, the design could be converted into a custom-designed chip. In all these scenarios, it will stimulate experimentation, and boost the adoption.

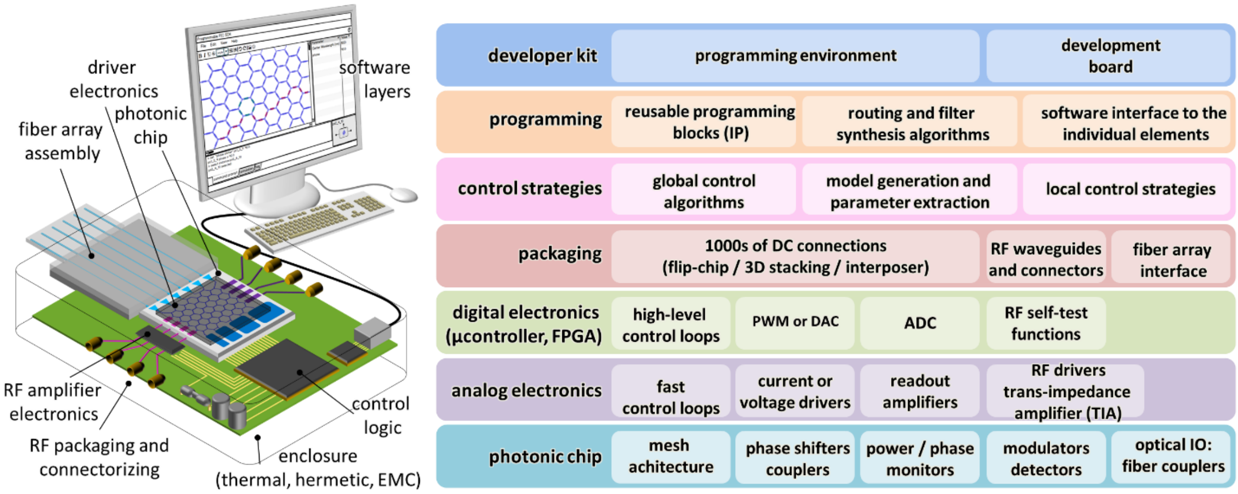

Figure 2: Technbology stack for programmable photonic circuits. Apart from the photonic and electronic chip, connected with packaging technology, there is a need for multiple layers of driver, control, configuration algorithms and programming tools.

Of course, a first requirement is that this technology becomes available. To realize the promise of such programmable photonic chips, the entire technology stack must be accessible to the users [5]. Like application-specific photonic circuits this requires a photonic chip, but also the electronic drivers, fiber connections and packaging technologies (including high-speed electronics if needed). But on top of that, programmable photonics needs additional software layers, starting with low-level management of the individual actuators and detectors in the circuit, to control and calibration routines (all elements in these circuits are analog and susceptible to fabrication variations). Users of these programmable chips will need synthesis algorithms to implement custom functionality such as wavelength filters, and define connectivity between building blocks and subcircuits (similar to placement and routing in electronic FPGAs). Also, like with programmable electronics, these design activities should be supported by a solid development kit that allows the users to inspect and debug the behavior of their photonic system. While the first hardware demonstrations are slowly taking shape, the software elements today are in an embryonic or even nonexistent state, and it will be interesting to observe their emergence and evolution in the coming years.

To conclude, we can go back to the question whether the world will need general-purpose programmable photonics? If we want to reap the same benefits of scale as with on-chip electronics, the answer is a definite Yes. The world needs photonic integration for the functionality it can provide (at a fundamental lower cost and power consumption), but to reach the same critical mass as integrated electronics, we need a much larger community that can innovate based on this technology. Photonic chips with a higher-level design interface, in the form of programmable software layers, can open up this technology to the much wider group of electronics and software engineering professionals, and even put photonic chips in the hands of the maker community.

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